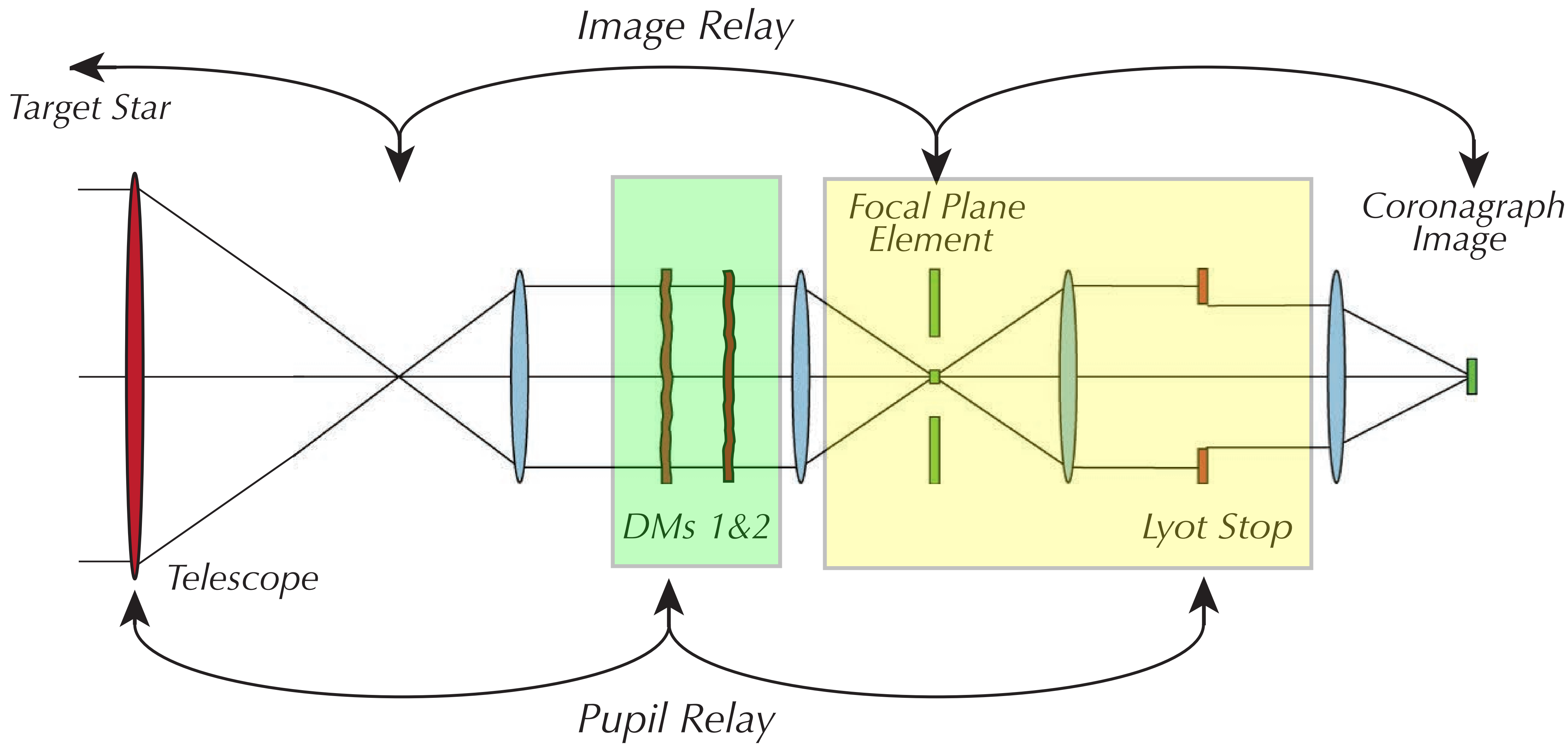
The hybrid Lyot coronagraph for the AFTA telescope

John Trauger
Jet Propulsion Laboratory / Caltech

Meeting 2.5 of the AFTA Coronagraph Working Group
Teleconference – 24 October 2013

Essential elements of the Lyot coronagraph



- *Sketch of the* ***actively corrected hybrid Lyot coronagraph*** *– all essential elements are represented here: the focal plane mask, pupil plane (Lyot) mask, and the pair of DMs.*
- *Coronagraph elements are highlighted in yellow, wavefront control elements in green.*
- *Wavefront control with a* ***sequential pair of deformable mirrors*** *in the collimated beam upstream from the coronagraph.*
- *Diagram unfolds the optical system and depicts powered elements as lenses for clarity.*

Coronagraph design trade space

- ***Global optimization of the coronagraph system**: we include as free parameters:*
  - *Thickness profiles on the focal plane occulting mask (metal & dielectric layers)*
  - *Shape and dimensions of the Lyot stop*
  - *Surface figure settings on each of the two DMs*
- ***Design trade metrics:** optimization target includes the following objectives:*
  - *Raw image contrast*
  - *Tolerance to pointing jitter and stellar diameters*
  - *Spectral bandwidth*
  - *Inner and outer working angles*
  - *Overall throughput*
  - *Engineering simplicity*

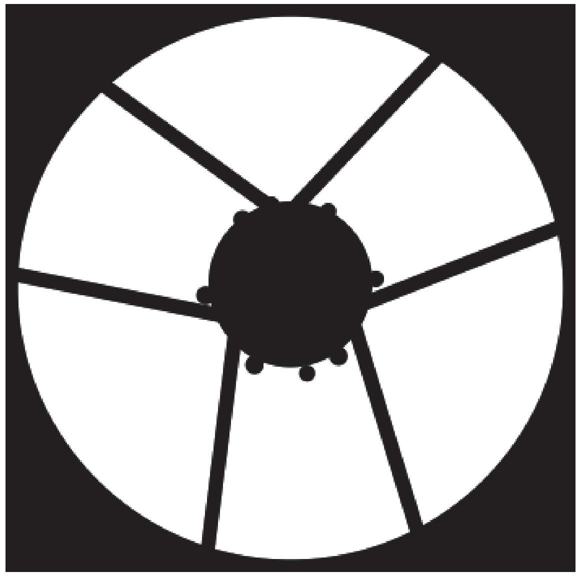
Coronagraph design optimization

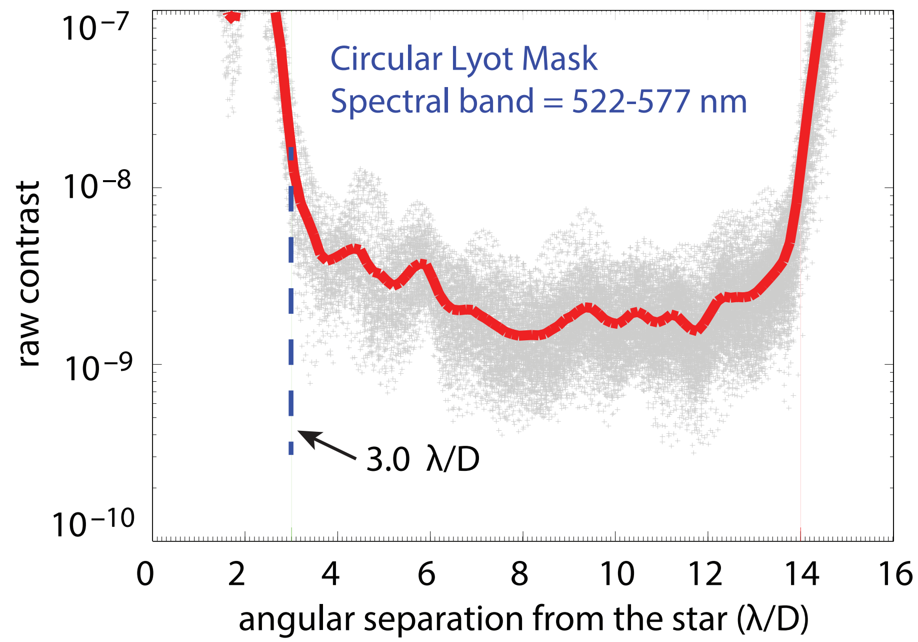
- ***Non-linear least squares optimization:***
  - *Focal plane and pupil plane masks and DM settings as free parameters*
  - *Iterative, small linear steps, method of steepest descent, parameter regularization*
- ***Design constraints:***
  - *AFTA 2.4 meter telescope (as supplied by John Krist on 8/21/13, with offset circular central obscuration, six SM support struts, zero surface figure and alignment errors)*
  - *Circular symmetric metal-dielectric hybrid Lyot focal plane occulter (symmetry is preferred for simplicity of manufacture).*
  - *Wavefront control with a pair of 48x48 DMs separated by one meter in a collimated beam.*
  - *Inner working angle = 3-4* λ/D *(*λ/D *= 550nm/2.4m = 47 milliarcseconds)*
  - $\delta\lambda/\lambda$ *= 10% spectral bandwidth centered at* λ *= 550 nm*
  - *1 millliarcsec stellar diameter (~angular diameter of the sun at 10 pc)*
  - *Pointing jitter as specified (1.6 mas rms "baseline", 0.8 mas rms "opportunity".*

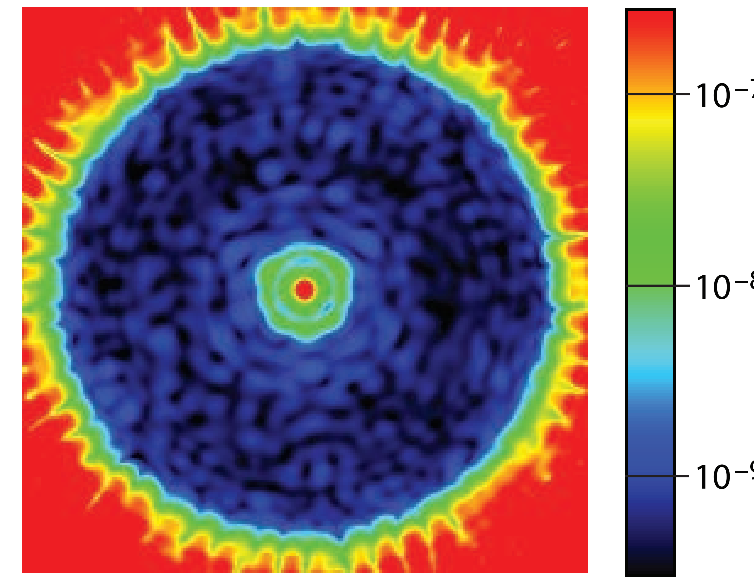
Coronagraph design optimization, continued ...

- ***Optimization goals:***
  - *High contrast, foregoing design trade metrics, minimal DM stroke.*
  - *Figure(s) of merit for coronagraph performance as defined by the AFTA TAC.*
- ***Optimization utilizes the available degrees of freedom in successive phases:***
  - *Adjust free parameters in an optimal sequence and in small linear steps*
  - *Pupil representation progresses from unobscured circular pupil, then adds central obscuration, then adds struts*
  - *DM settings progress from single DM, then two DMs with simple rules, then two DMs with numerically optimized settings.*

AFTA coronagraph design as of ACWG 2.0



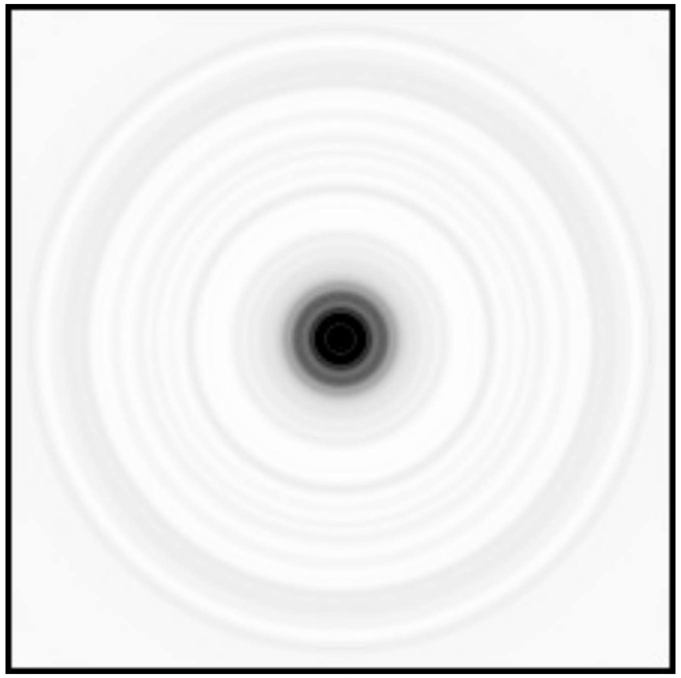




- *A **hybrid Lyot coronagraph** design is being optimized for a 2.4 meter telescope with central obscuration and six SM support struts*
- *Design utilizes a circular metal-dielectric Lyot focal plane mask plus Lyot stop and wavefront control with a pair of 48x48 actuator DMs, presumes ACCESS level pointing control (better than 0.3 mas).*
- *Designed for **3.0 λ/D inner working angle and 10% spectral bandwidth**.*
- *Performance predictions are based on optical models that have been validated to the 2e-10 contrast level in TDEM/HCIT demonstrations (Trauger et al.).*

Global optimization: focal plane and pupil plane elements

- *Metal-dielectric (nickel and MgF2) focal plane mask controls both the real and imaginary parts of the star's point spread function. The intensity transmittance is illustrated here. Average transmittance in the dark field is 90%.*
- *Pupil plane (Lyot) mask has cutouts for the central obscuration and the six support struts. Lyot throughput is 41%.*



Focal Plane Element

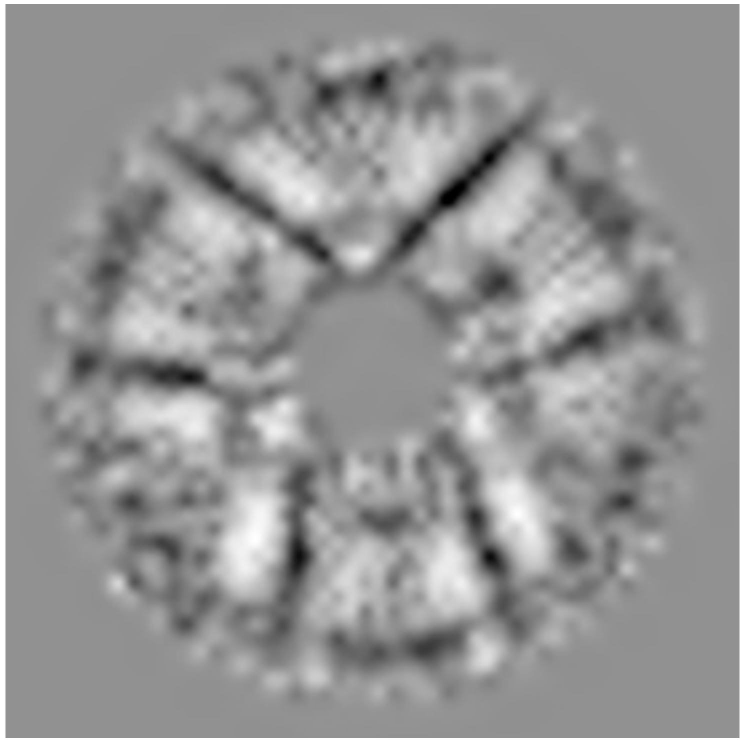
Pupil Plane Element

Coronagraph optimization: wavefront control & Lyot stop

- *Shown here, the wavefront phase modulations introduced by the two 48x48 DMs with the foregoing occulting and Lyot masks. Surface displacements are 0.26 μm PV..*
- *Note that these DM settings show a similarity to the ACAD strategy (Pueyo). In fact, the pair of DMs can compensate entirely for the diffraction from the six struts using a circular symmetric Lyot stop (w/o cutouts for the struts), but this would require an undesirable large ~5 μm PV of DM surface displacement.*

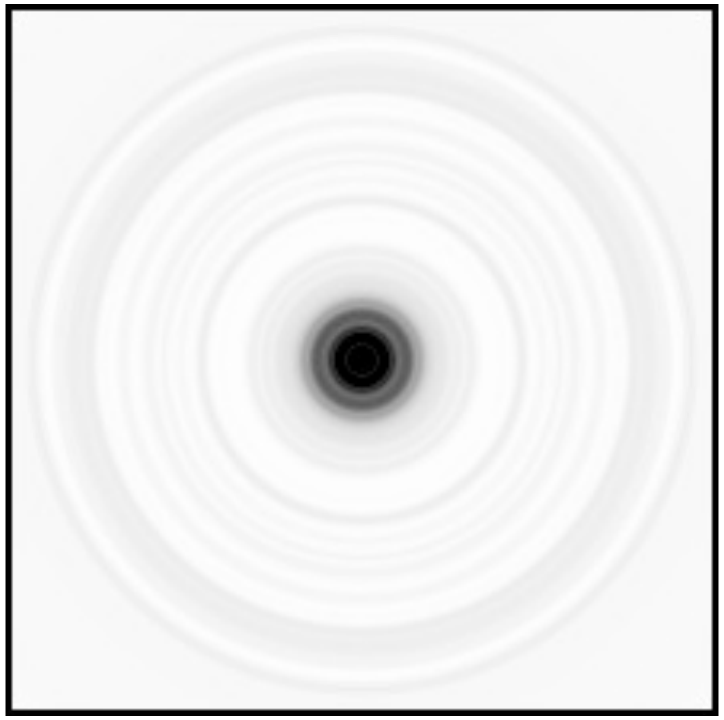
Lyot stop (grey)

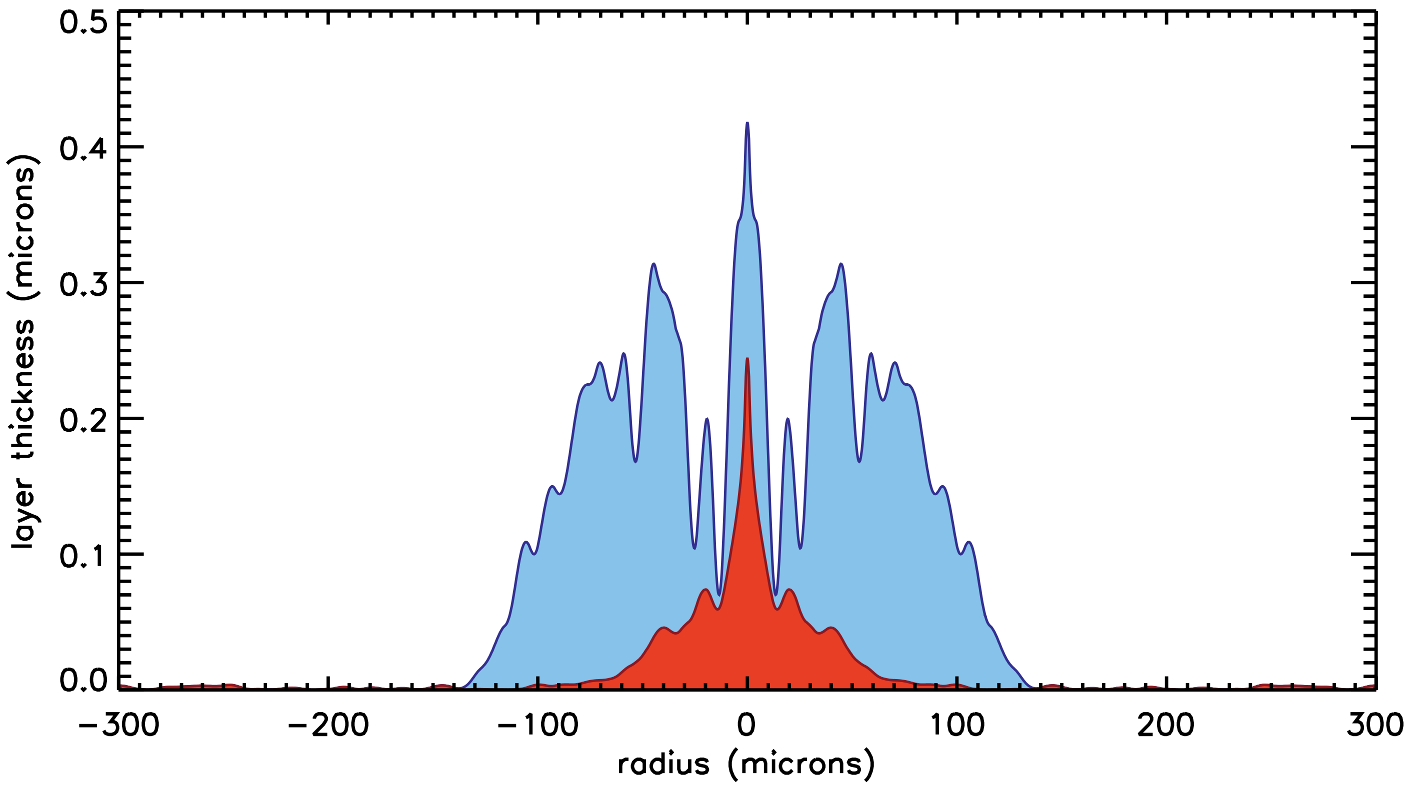
delta phase for DM1



delta phase for DM2

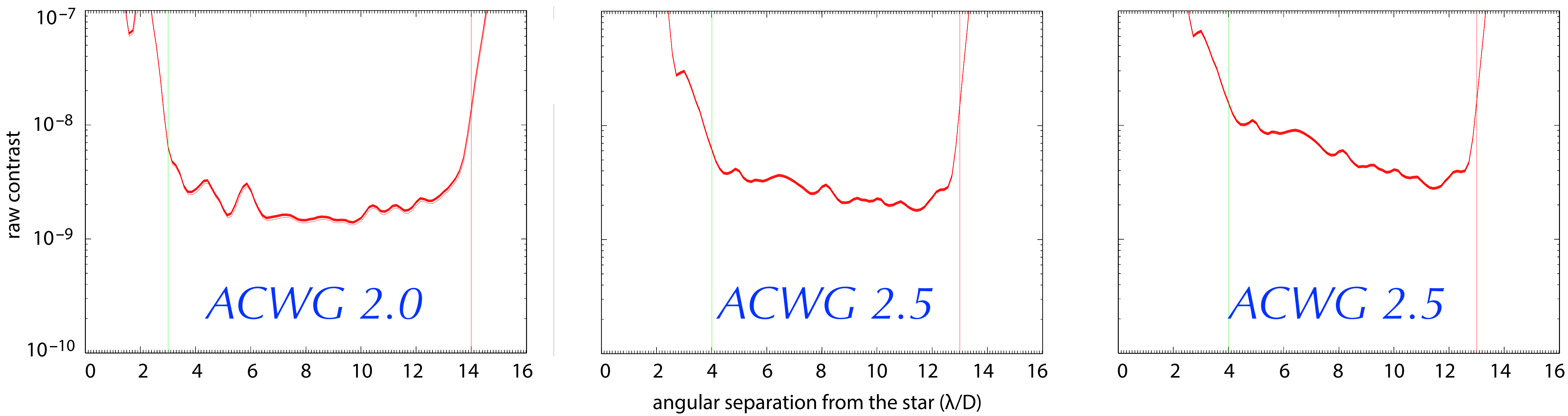
Circular hybrid Lyot mask





- *Above left, the attenuation pattern of a representative circular mask. Mask is designed for a 3 λ/D inner working angle, and optimized for the AFTA pupil.*
- *Above right, the radial cross section "sand diagram" of the superimposed, thickness-profiled metal (red) and dielectric (blue) layers. Note that the vertical axis has been expanded by a factor of 700 for clarity – the pattern is actually quite flat.*
- *Factoid: very little material is required:*
  - *Peak thickness of nickel layer is 0.24 microns. Total material volume = 920 cubic microns = 8.2 nanograms*
  - *Peak thickness of MgF2 layer is 0.28 microns. Total material volume = 6900 cubic microns = 19.5 nanograms.*

Coronagraph trades, now with larger pointing jitter for ACWG 2.5



"ACCESS"

- *Circular hybrid mask*
- *2.4 meter AFTA Pupil*
- *IWA = 3.0 λ/D*
- *Jitter = ACCESS (~0.3 mas)*
- *Stellar diameter = 1.0 mas*
- *Central λ = 550 nm*
- *Bandwidth = 10%*
- *DM P-V = 0.26 microns*
- *Coro throughput = 37%*
- *360 degree field of view*
- *No polarizers*

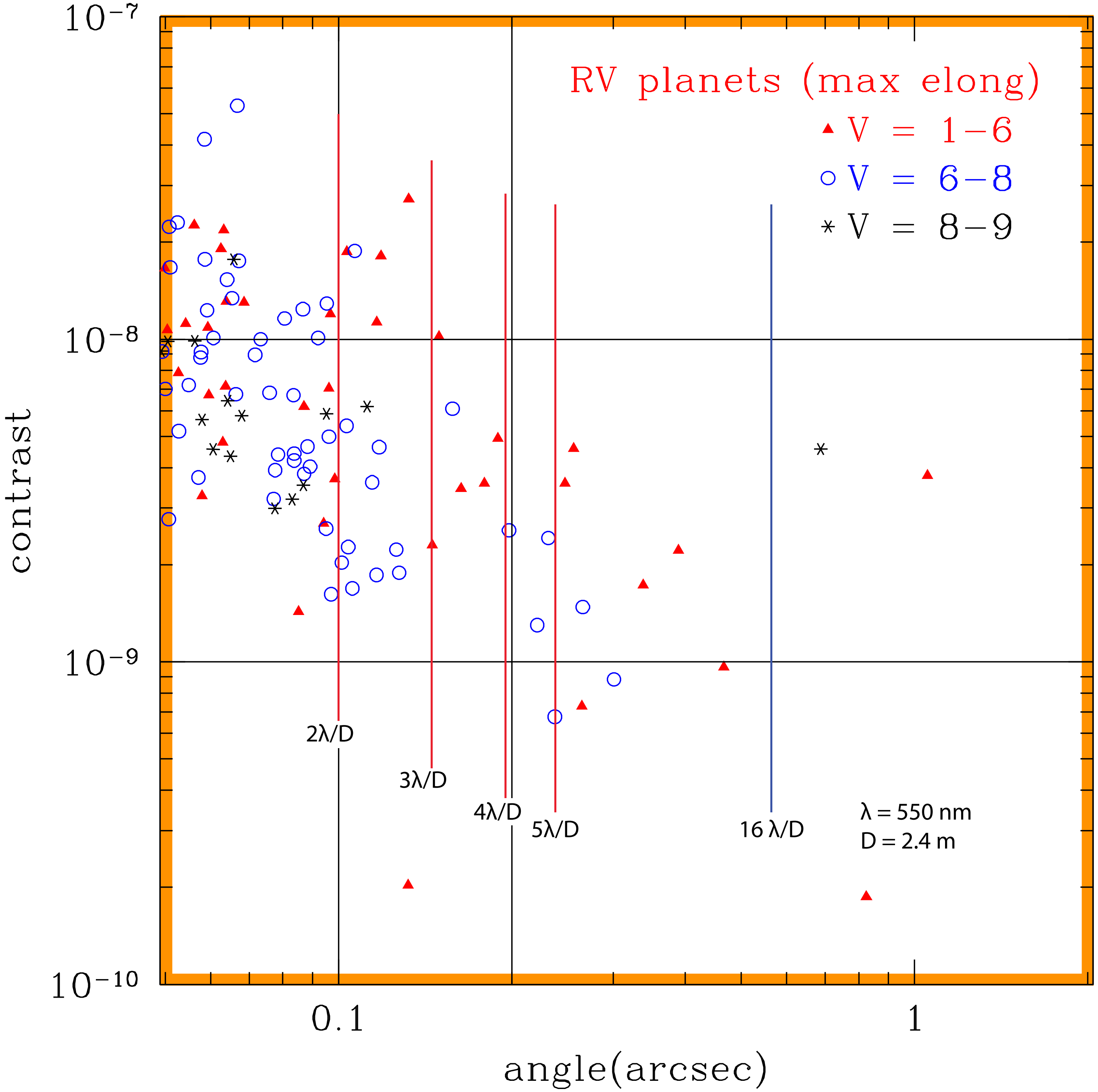
"Opportunity"

- *Circular hybrid mask*
- *2.4 meter AFTA Pupil*
- *IWA = 4.0 λ/D*
- *Jitter = 0.8 mas*
- *Stellar diameter = 1.0 mas*
- *Central λ = 550 nm*
- *Bandwidth = 10%*
- *DM P-V = 0.26 microns*
- *Coro throughput = 37%*
- *360 degree field of view*
- *No polarizers*

"Baseline"

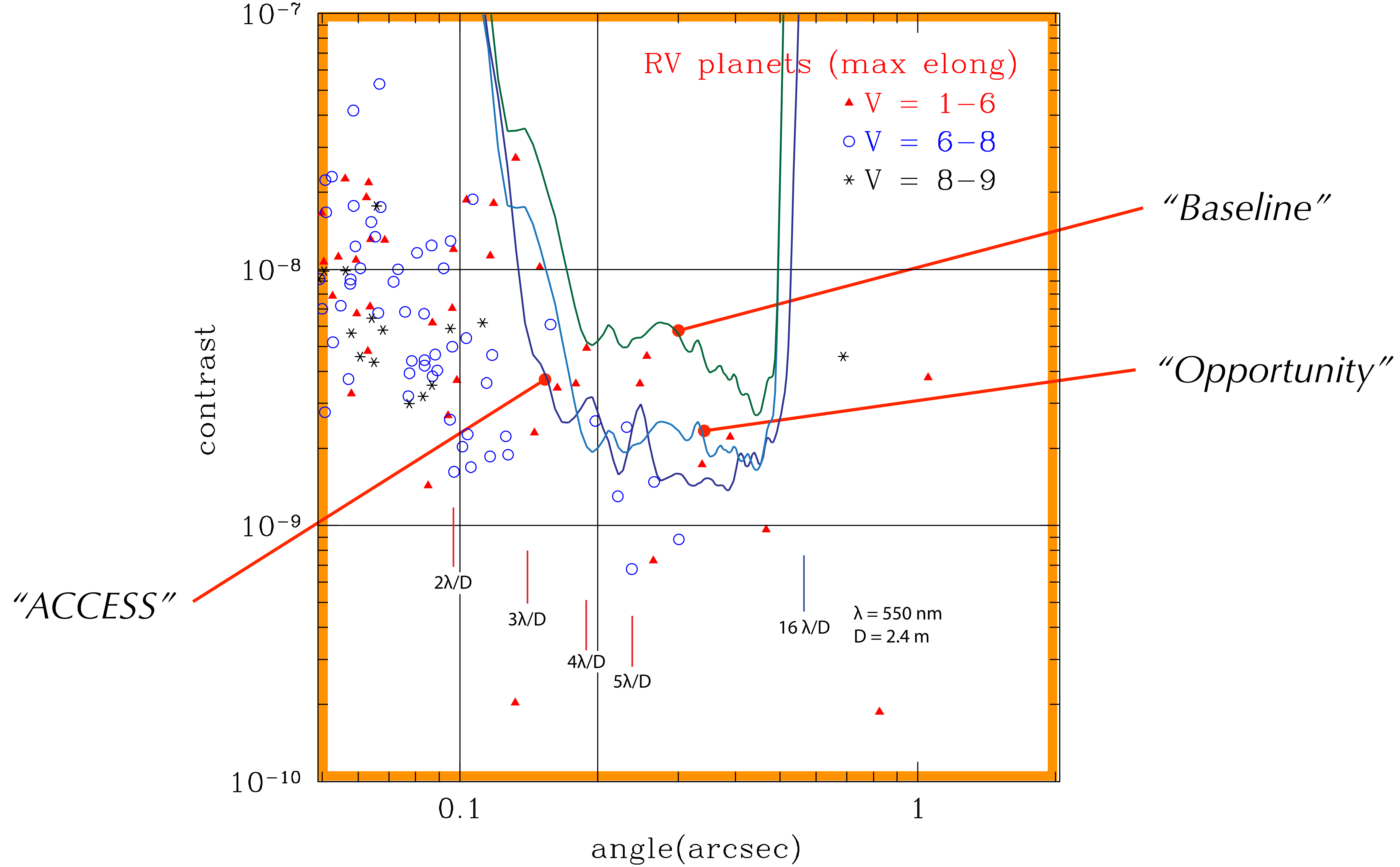
- *Circular hybrid mask*
- *2.4 meter AFTA Pupil*
- *IWA = 4.0 λ/D*
- *Jitter = 1.6 mas*
- *Stellar diameter = 1.0 mas*
- *Central λ = 550 nm*
- *Bandwidth = 10%*
- *DM P-V = 0.30 microns*
- *Coro throughput = 37%*
- *360 degree field of view*
- *No polarizers*

Known RV planets: Traub chart (10/18/13)



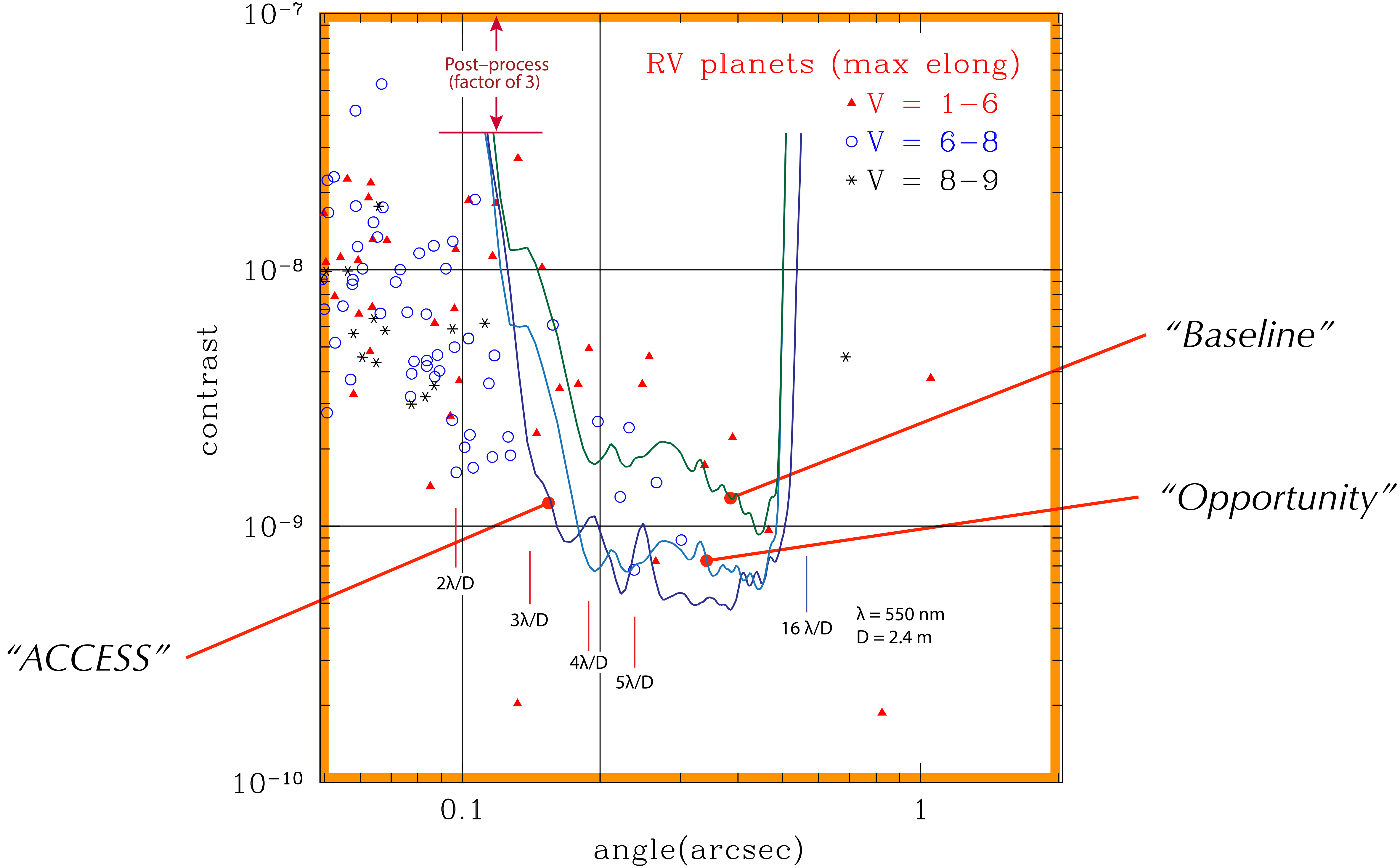
- *Relative brightness vs. separation for the ACWG list of RV target exoplanets.*
- *Provides a standard reference for the evaluation of Must M2.*

Known RV planets: comparison with raw coronagraph contrast



- *Raw contrast curves for the "Baseline", "Opportunity", and "ACCESS" coronagraph design are superimposed on the Traub RV chart.*
- *Provides a preliminary indication that "ACCESS" and "Opportunity" meet M2 without post-processing enhancement.*

Known RV planets: comparison with post-processed contrast



- *Post-process shortcut assessment: offset contrast curves downward by a factor of 3.*
- *Provides preliminary indication that "Baseline" meets M2 and that "ACCESS" and "Opportunity" provide W1a science enhancements beyond M1.2.*

Hybrid Lyot Status: Musts and Wants

- M1: Science requirements. Preliminary assessment indicates the "Baseline" design meets M1.1 and M1.2. Clarifications from the project and further analysis are needed to evaluate M1.3,4,5,6.
- M2: Meets DCIL. Yes.
- M3: TRL gates. Yes – with reference to tomorrow's ACWG2.5 hybrid Lyot technology presentation.
- M4: Ready for TAC briefing. Yes.

- W1a: Preliminary assessment indicates the "Opportunity" design will enhance M1.2 science, while "ACCESS" design captures nearly all RV planets beyond 3 λ/D.
- W2: Relative demands, sensitivities, TRLs, complexity, operational difficulties. Further information and analysis are needed to evaluate W2a,b,c,d,e.
- W3: Relative cost to reach TRL gates. TBD.

Status: hybrid Lyot coronagraph for the AFTA telescope

- *"Baseline" design has been forwarded to John Krist for project analysis.*
- *Further design optimizations are continuing – among the objectives:*
  - *Better contrast vs. IWA trade for science productivity.*
  - *Increased spectral bandwidth – to 15-20%.*
  - *Minimal DM peak-to-valley stroke.*
  - *Increased throughput of both focal plane mask and Lyot stop.*
- *Preparations for fabrication of the mask are in progress with JPL IRAD funding:*
  - *Progress and expectations to be summarized in tomorrow's ACWG2.5 technology presentation.*
  - *We expect to have masks ready for testbed demonstrations by mid-FY14.*

Backup Slides

Exoplanet Science Requirements

1. (Threshold) The coronagraph will operate from 430 to 980 nm in >10% bandpasses. The imager will provide at least five 10% filters at roughly 450, 550,650, 800, 950 nm and to image separately or simultaneously in two polarization channels. The spectrograph will provide R~70 from 600 to 950 nm in at least 10% coverage per setting. The imager will have a FOV of 3”x3” (with no requirement on the coronagraph OWA) and sampling 50% better than Nyquist at 450 nm. The ifs will be Nyquist sampled at 600 nm and have a FOV of at least half the coronagraph OWA
   1. With these parameters, it will require 5 spectrograph exposures for full coverage
   2. It is a strong goal to cover at least 15% bandpass in a single coronagraphic setup to allow a broad absorption line and surrounding continuum to be measured in a single exposure, and reduce number of needed exposures to 4
   3. It is recognized that the residual speckle halo may be polarized, the requirement is only to potentially measure polarization of bright debris disks that are significantly above the residual halo
2. (Baseline) AFTA will be capable of spectroscopically characterizing at SNR=10 per resolution element from 600-850 nm at least 6 previously-known Doppler planets in 3 months of mission time (assuming orbits are known and observations are targeted to the most favorable observing conditions) distributed over the full 5 year mission, assuming grey planetary albedo of 0.1 and attenuation of speckle noise by 1/10

- Note that there’s no explicit requirement on spectra of previously-unknown planets, though models indicate that a subset of the discoveries will be characterizable

Exoplanet Science Requirements

3. (Baseline; threshold is depth=13) AFTA shall achieve a total search depth for objects from r1=4 RE to r2=13 RE and 0.1<a<5 of 130 over a survey of 200 stars observing at 550 nm with one visit per star and a total survey time of up to 2 months
    - We probably need to specify an albedo (critical) and eccentricity (not as critical), recommend 0.2; or Cahoy values
    - For a reasonable Kepler-like radius distribution extrapolated out to 5 AU, this lets the mission find >10 giant planets for most smooth depth of search functions
    - These values need to be verified by a Monte Carlo crosscheck
    - Savransky and Macintosh will evaluate these quantities for several toy coronagraphs.
4. (Baseline) AFTA shall achieve a total search depth for objects of r<4RE of 5 over a survey of 200 stars observing at 550 nm with four visits per star and a total survey time of up to 2 months

- For the Kepler distribution this would discover ~4 sub-neptune planets
- Total search depth for objects of r<2RE is a important 'extra' science capability for selection, with a desirable value being >4

Disk Science Requirements

5. Threshold requirement: AFTA will be capable of detecting a disk of 100x our solar system's zodiacal level at SNR=5 per resolution element at 2 AU separation around a star 8 pc away at 450 and 800 nm

- In Traub calculation (see next page) this is a contrast of 6.4e-9 per resolution element; assuming x10 suppression of the speckle halo that requires 1.3e-8 raw contrast
- This corresponds to a IWA of 0.25 arcseconds.

6. Baseline requirement: AFTA will be capable of detecting a disk of 10x our solar system's zodiacal level at SNR=5 per resolution element at 1 AU at 450 nm at 8 pc

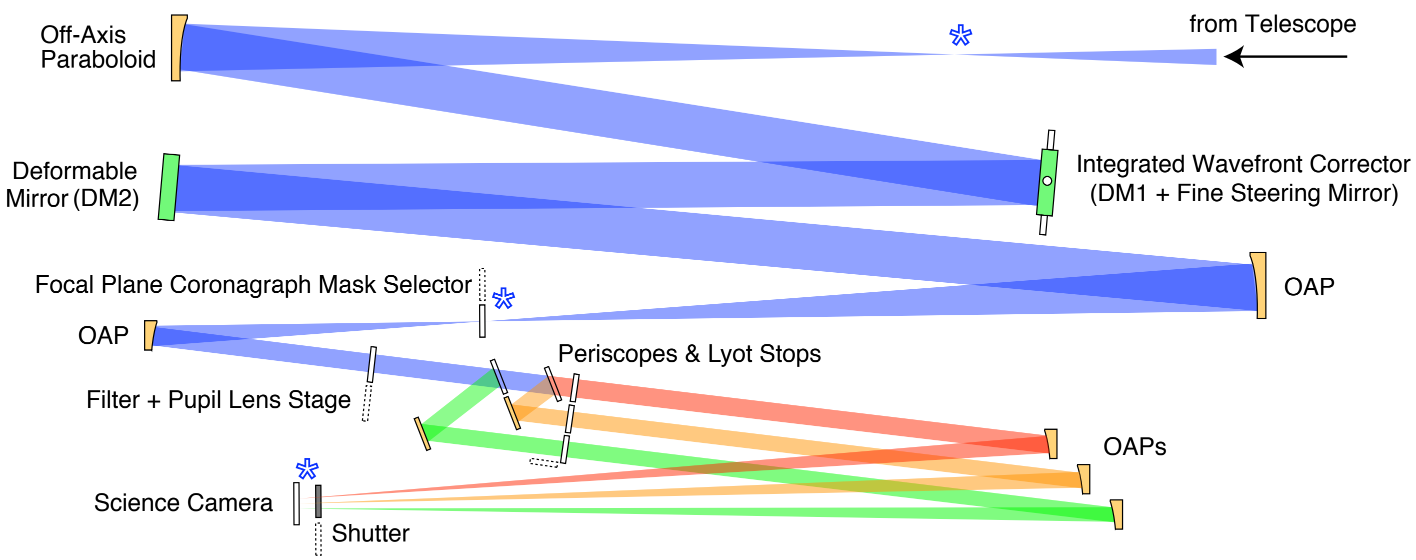
- In Traub calculation (see next page) this is a contrast of 3e-9 per resolution element; assuming x10 suppression of the speckle halo that requires 6e-9 raw contrast
- This corresponds to a very challenging IWA of 0.13 arcseconds
- This does not have to be achieved over a full 360 degree field of view, could be achieved in multiple coronagraph or spacecraft orientations

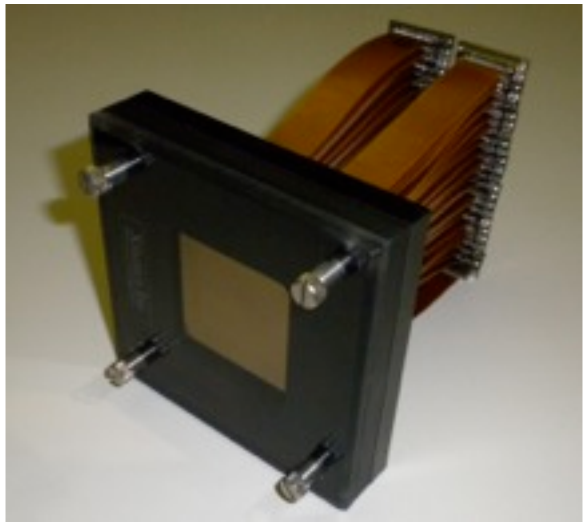
PSF subtraction

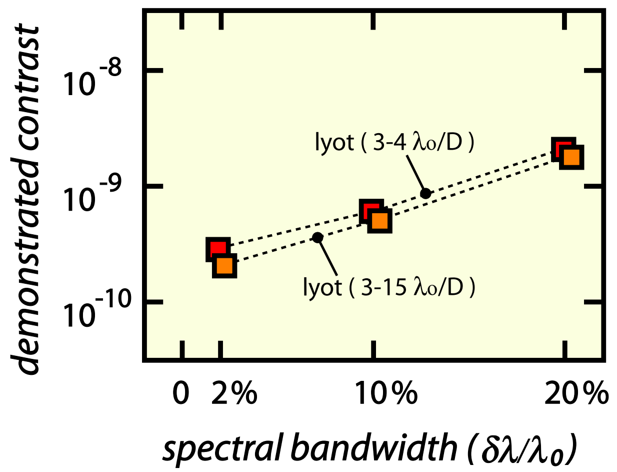
- Telecon with Soummer, Perrin, Greene, Macintosh, Traub
- PSF subtraction depends both on algorithms (which have had good progress), diversity (distinguishing characteristics of planets vs speckles) and stability
- Observing scenarios need to be considered
- In imaging mode, the signal to noise for the planet is set by the quadrature sum of the poisson photon noise, readnoise, and residual speckle noise
- Speckle noise after psf subtraction is assumed to be 1/10 of the pre-subtraction noise level. This gives a speckle noise 5-sigma contrast floor equal to ½ of the average speckle intensity contrast
- For simulation purposes, we discussed arbitrarily scaling Krist contrast by x2
- If time permits, we will run planet-detection Monte Carlos assuming x3 speckle suppression for comparison / as an additional factor in downselect

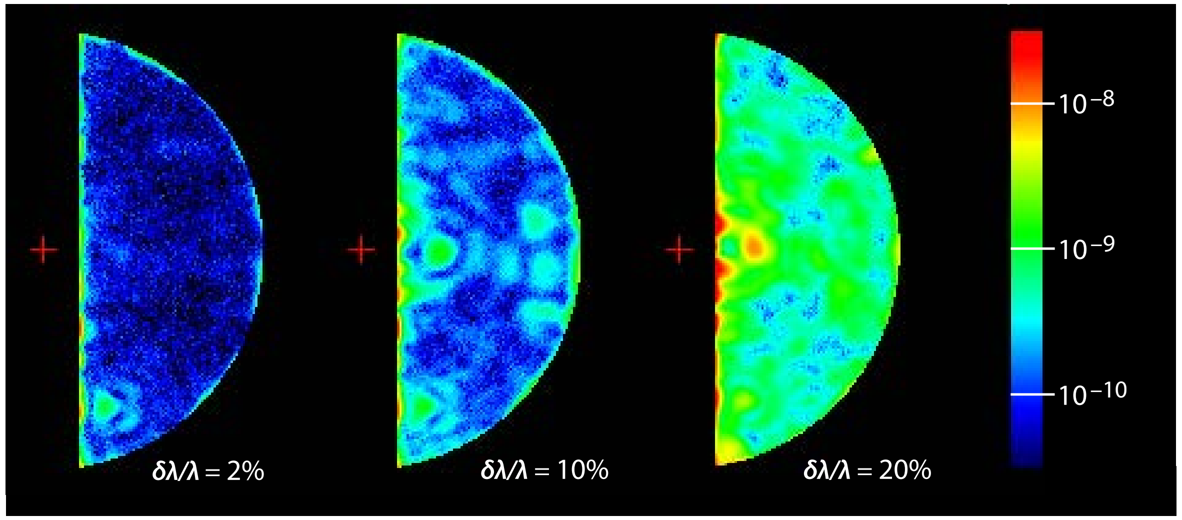
- Project or SDT to provide a standard working target list

Technology heritage: ASMCS and SAT/TDEM demonstrations





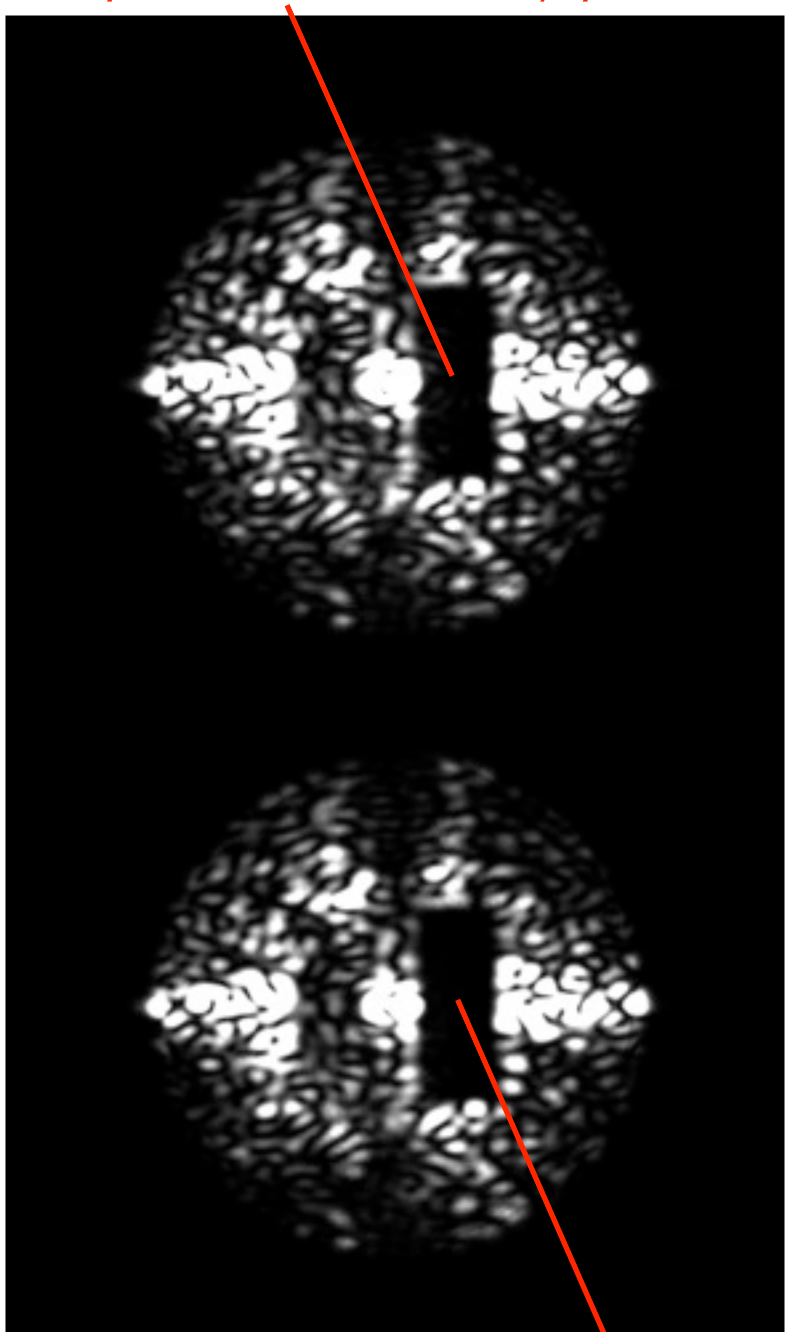




- ***ACCESS optical layout*** *is functionally similar to the AFTA coronagraph.*
- *A pair of* ***protoflight qualified deformable mirrors*** *(a 48x48 actuator DM is shown) manipulate the wavefront amplitude and phase to create a high contrast dark field.*
- *Representative* ***Lyot coronagraph*** *raw contrast performance, as demonstrated in the NASA SAT/TDEM program, provides the basis to forecast ACCESS mission performance with post-processing of images.*

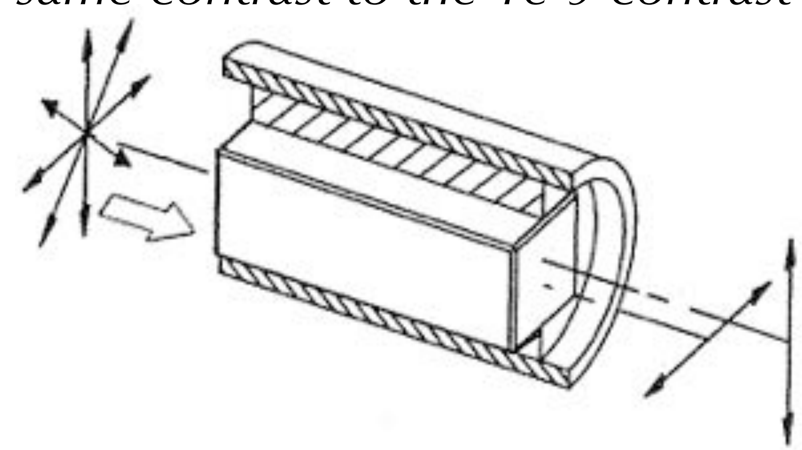
The hybrid Lyot coronagraph is insensitive to polarization

Extraordinary polarization (displaced 4.5 mm by prism)



Ordinary polarization (undeviated by prism)

- *No polarizers have been used for the source "star" in any of the hybrid Lyot coronagraph demonstrations for ASMCS and SAT/TDEM programs.*
- *HCIT testbed demonstrations have been carried out for several years with a beam deviating calcite prism placed in front of the science CCD focal plane.*
- *Shown at left: speckle nulling is performed on just one of the images in monochromatic light. The lower image is undeviated by the crystal, while the upper image, in the orthogonal polarization, is displaced 4.5 mm by the crystal. Both are imaged simultaneously by the science CCD camera.*
- *In general, the dark field in the orthogonal polarization shows the same contrast to the 1e-9 contrast level.*

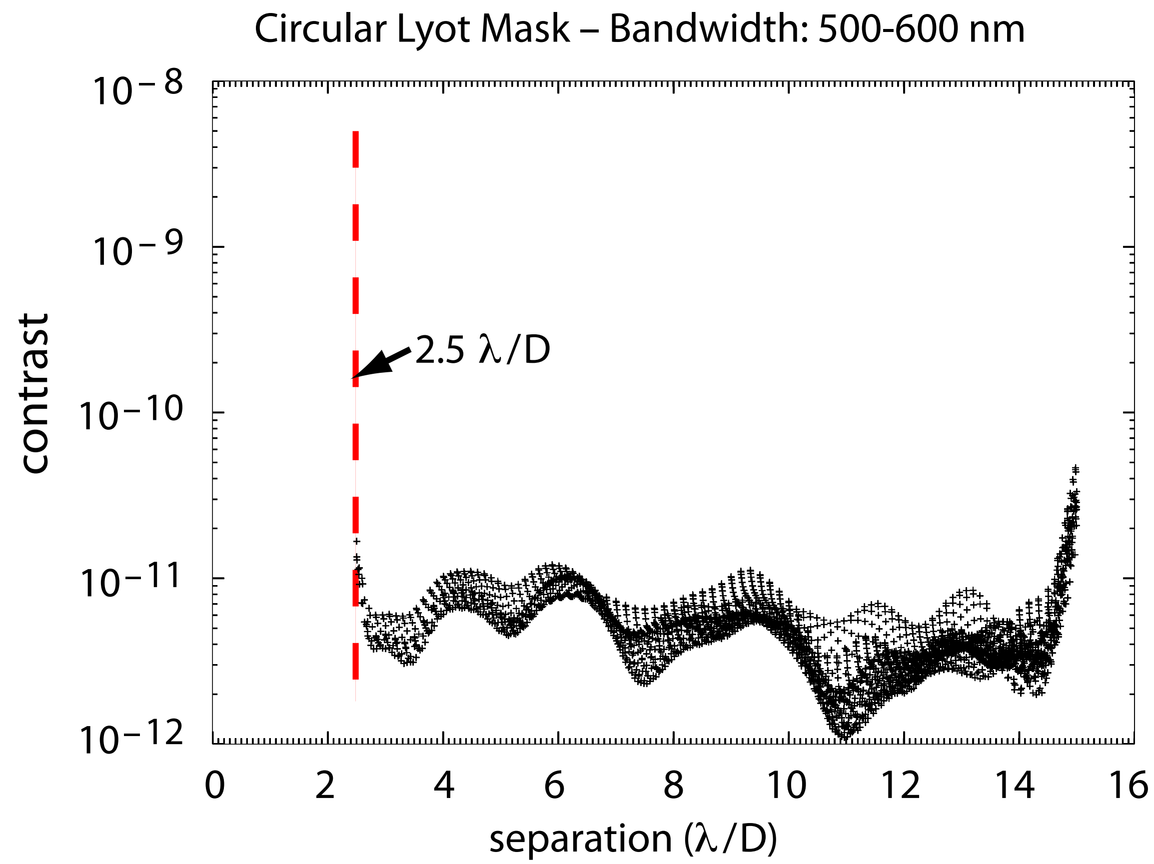


Placed just in front of the HCIT coronagraph camera, a calcite Beam Displacer splits the input unpolarized beam of light into its two orthogonally polarized components which exit parallel to each other.

Unobscured telescope apertures are preferred for high contrast coronagraphy

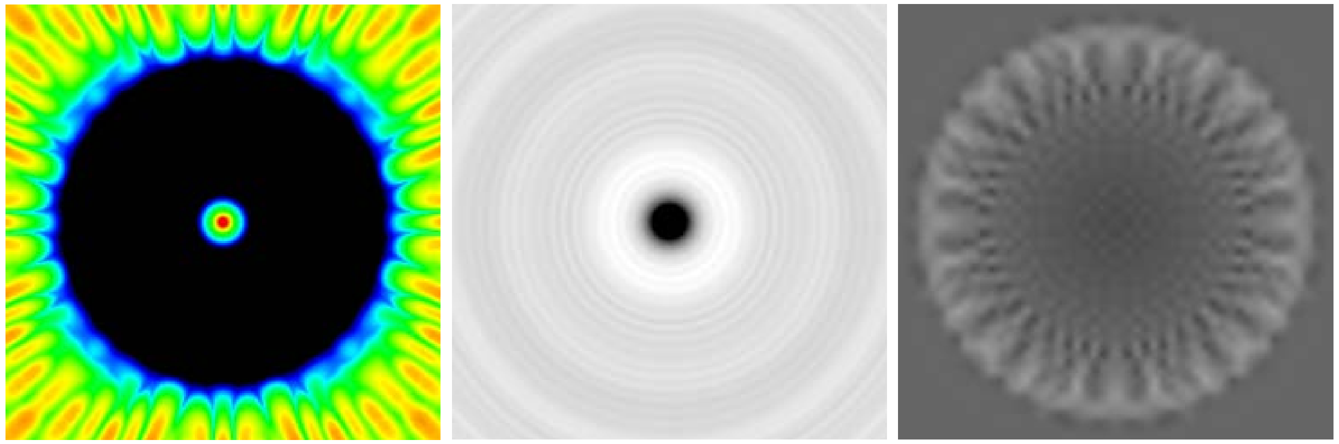
Complex Apodization Lyot Coronagraphy

John Trauger, Brian Gordon, John Krist, Dimitri Mawet, Dwight Moody (Proc.SPIE 8442-04, 2012)



Computed performance for a newly designed circular complex apodized Lyot mask:

- *As for previous linear mask designs, the thickness profiles of the metal and dielectric layers are optimized simultaneously with the wavefront phase control of a single 48x48 DM.*
- *Focal plane mask is a layer of nickel plus a layer of cryolite superimposed on a fused silica substrate.*
- *These two layers provide the degrees of freedom to control both the real and imaginary parts of the optical wavefront.*
- *Inner working angle is 2.5 λ_0/D. Note that a full 360^O dark field has been created with a single deformable mirror.*
- *Contrast in the 500-600 nm ($\delta\lambda/\lambda_0 = 18\%$) spectral band is 5.3×10^{-12} in both the inner 2.5–3.5 λ_0/D annulus and averaged across the entire dark field extending from radii of 2.5 to 15 λ_0/D.*

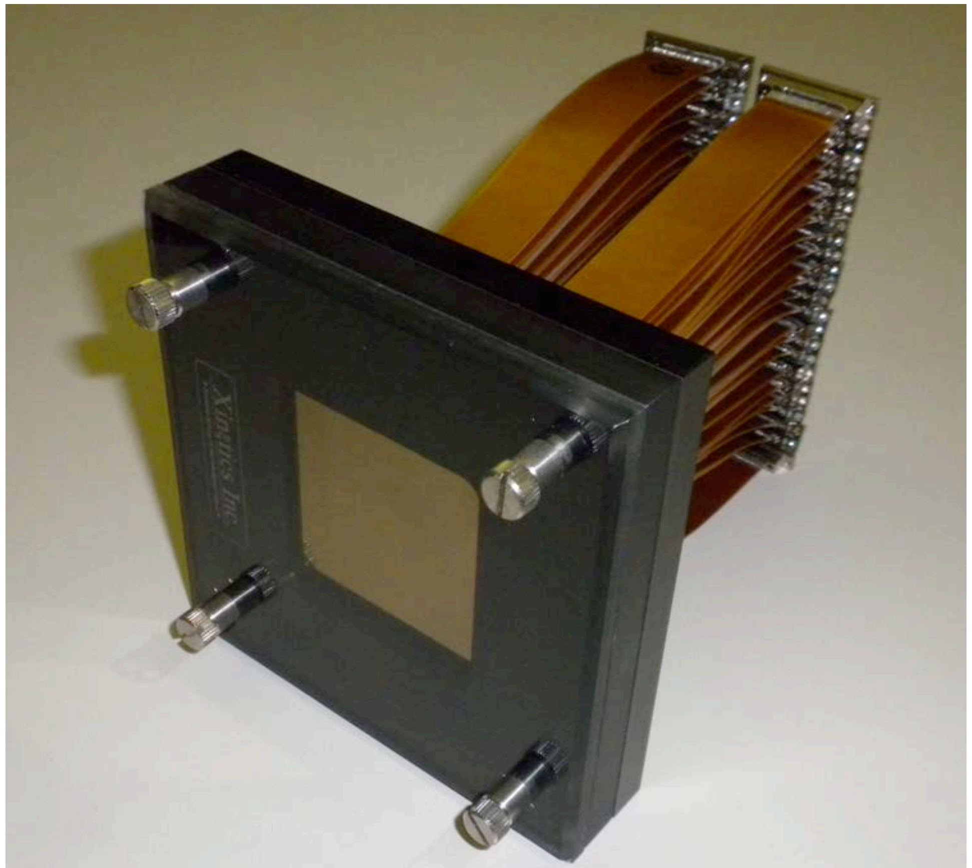


Left: Raw contrast in the dark field is displayed with a logarithmic stretch from 10^{-11} to 10^{-7}.

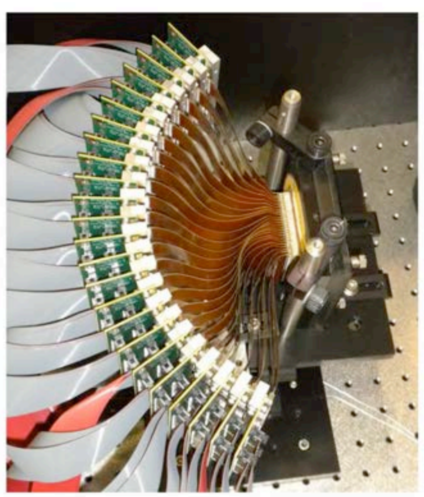
Center: Intensity transmittance profile of the complex apodized focal plane mask is displayed with a linear stretch from zero to 1.

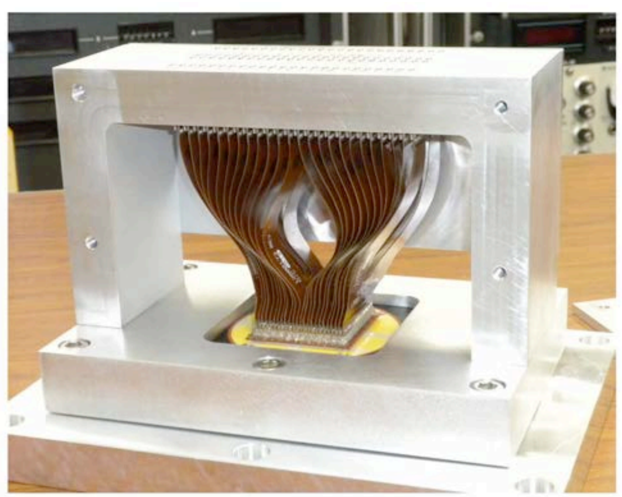
Right: Corresponding surface setting on the deformable mirror is displayed with a linear black-to-white stretch of 40 nm.

Measured DM characteristics are the basis for wavefront control



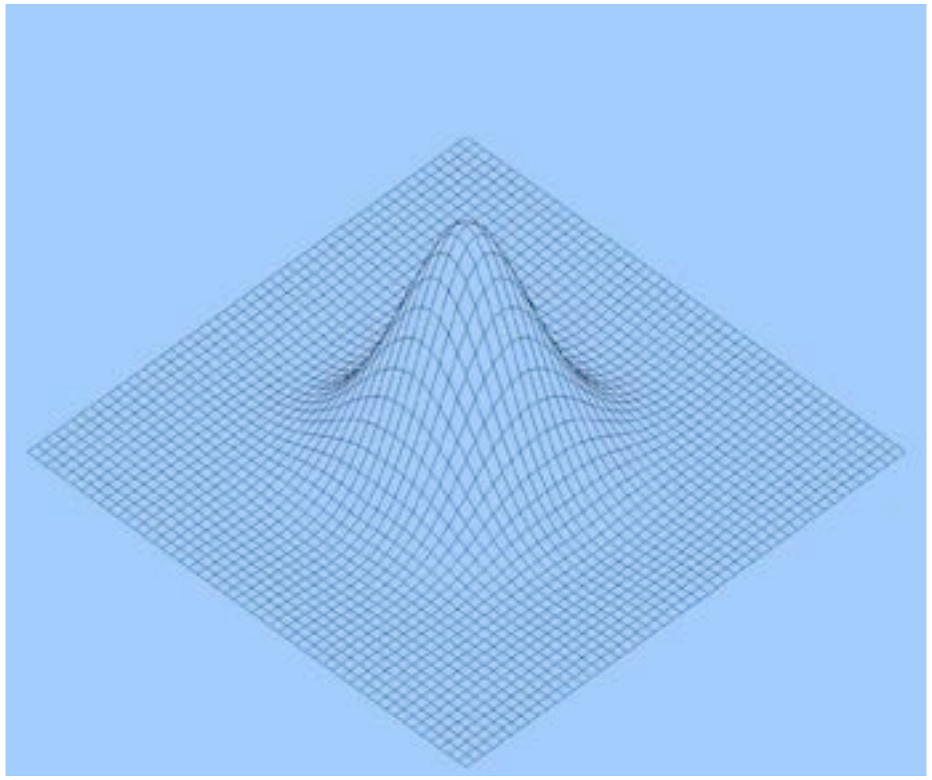
- *Shown is a* ***48x48 actuator*** *PMN electrostrictive deformable mirror.*
- *This DM is flight-ready, has completed a* ***protoflight qualification*** *3-axis vibe test to 10.8 grms.*
- *Mirror facesheet is fused silica polished flat to* ***5 nm rms surface*** *figure in the unpowered state.*
- *On the backside, a 50x48 pin grid header provides electrical connections to each of the 2304 actuator elements.*
- *Flex circuits carry the interconnects to 48 flight-quality 51-pin connectors.*
- *Manufactured by AOA Xinetics.*

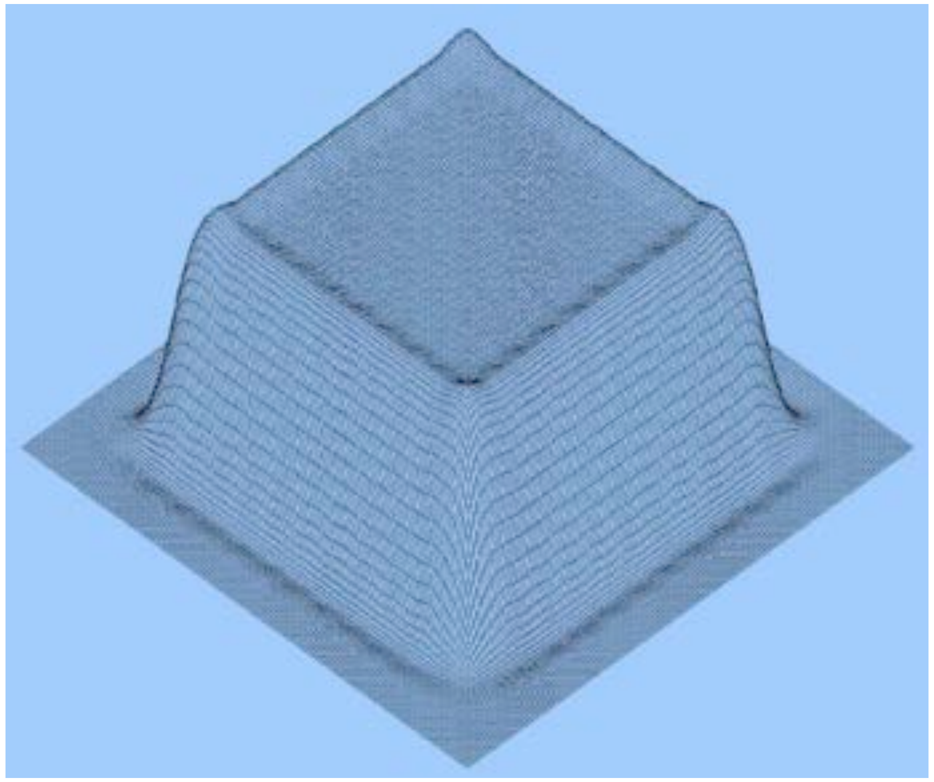




- *Above, the 48x48 DM is mounted on the Zygo bench for optical tests. Flex ribbon cables fan out to the 2304-channel electronic driver system.*
- *Above right, the DM is clamped into its shake test fixture, with all flex connectors anchored as shown, prior to adding shear plates, ready for 3-axis random vibe tests.*

Measured DM influence functions





- *At left, the* ***surface influence profile*** *for a single actuator. Surface displacement relaxes typically to 10% of the central displacement at the nearest neighboring actuators (1 mm away).*
- *Actuator pitch is 1/mm, surface profile has been measured in a vacuum interferometer with 0.1 x 0.1 mm sample density.*
- *At right,* ***linear superposition*** *of individual influence functions predicts overall DM surface displacement: shown is the surface figure result for the simple addition of an 11x11 array of actuator influence functions.*

Simplicity favors the Lyot coronagraph

- ***Minimum number of critical optical elements*** *(6) between the star and coronagraph that are subject to* ***super-tight*** *wavefront control, beam walk, polarization effects.*
- *Minimum optical elements favors* ***higher throughput*** *and* ***fewer critical alignments****.*
- *There are* ***no high-angle reflective elements****, minimizes polarization effects internal to the coronagraph.*
- *There are* ***no transmissive elements*** *upstream of the focal plane occulter, i.e., there are no apodizers or polarizers, avoids dispersion.*
- *The* ***critical apodization is captured*** *on a small occulting mask, which is one metal and one dielectric thin film layer on a glass substrate, stable and robust for flight.*
- ***No optical distortions*** *are introduced from sky to science focal plane, simplifies iterative wavefront sensing and control.*
- ***End-to-end optical propagation calculations*** *(Fresnel approximation) and* ***system optical tolerancing*** *are relatively straightforward.*
- ***Minimizes complexity!!*** *Parts count, engineering interfaces, mutual alignments snowball in the buildup of assembly fixtures and metrology, alignment tolerances, failure modes and risk analysis, engineering coordination and reviews, subsystem integrations and tests – and these ultimately increase the cost, mass, schedule, and overall risk of the instrument implementation.*

End